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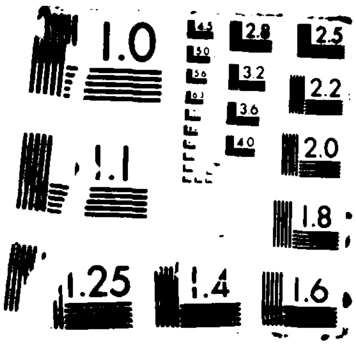
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DEVELOPMENT OF A SMALL SCALE TEST APPARATUS FOR THE EVALUATION OF THERMAL BARRIER MATERIALS

J.A. Hiltz - D.E. Veinot

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DEVELOPMENT OF A SMALL SCALE TEST APPARATUS FOR THE EVALUATION OF THERMAL BARRIER MATERIALS

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ABSTRACT

A small scale test apparatus has been constructed and used to evaluate the relative ability of four thermal barrier materials to protect aluminum from heat damage. The apparatus used 30 x 30 cm (1 ft x 1 ft) 0.64 cm (0.25 in) aluminum panels. Several configurations of the glass and ceramic fiber cloth barrier materials (Startex 6N, Startex 4N, SilTemp, and Claretex 1925 B567) were tested to determine the degree of protection provided by the thermal barrier materials. The results obtained with the small scale apparatus have been correlated with those obtained with a modified ASTM E119 apparatus at the Fire Research Section of the National Research Council of Canada. Although the results from the small scale tests do not compare with those from the ASTM E119 test in an absolute sense, they give the same relative ranking of the ability of the barrier materials to protect aluminum from heat damage. This suggests that inexpensive small scale testing can be used to screen and rank the ability of different materials and combinations of materials to protect an aluminum substrate from heat damage.

RÉSUMÉ

Un appareil d'essais à petite échelle a été fabriqué et utilisé pour évaluer l'aptitude relative de quatre matériaux de barrière thermique à protéger l'aluminium de la chaleur. Le dispositif utilisait des panneaux d'aluminium de 30 x 30 cm (1 pi x 1 pi) x 0.64 cm (0.25 po). Plusieurs configurations de matériaux de barrière en tissu de fibres de verre et de céramique (Startex 6N, Startex 4N, SilTemp et Claretex 1925 B567) ont été éprouvées en vue d'établir leurs divers degrés de protection. Les résultats obtenus à l'aide du dispositif d'essai à petite échelle ont été mis en correlation avec ceux provenant d'un appareil ASTM E119 modifié utilisé à la Section des recherches sur la prévention des incendies du Conseil national de recherches du Canada. Bien que les résultats des essais à petite échelle ne se comparent pas à ceux de l'essai ASTM E119 sur le plan absolu, ils révèlent néanmoins le même degré relatif de protection de l'aluminium à la chaleur de la part des divers matériaux de barrière. Cela permet d'avancer qu'un essai peu coûteux à petite échelle peut permettre de trier et de classer les possibilités de divers matériaux et combinaisons de matériaux en ce qui a trait à la protection d'une sous-couche d'aluminium contre les dommages provoqués par la chaleur.

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1.0 INTRODUCTION

In order to reduce topside weight on Naval vessels, aluminum alloys, which have high strength to weight ratios, have been used instead of steel for superstructure materials on some Canadian Naval ships. The use of aluminum is not without drawbacks however, as the aluminum alloy used (6061) has a melting range between 582 and 652°C and suffers severe loss of strength when exposed to temperatures above 300°C. The loss of strength of aluminum in a fire situation can have catastrophic effects, as it reduces the load carrying ability of the superstructure. In the worst case, this can result in the collapse of the superstructure. Heat transfer through aluminum can take place rapidly allowing a fire to spread quickly. The British experience in the Falklands conflict (1) served to bring these potential problems with the use of aluminum alloys into focus.

Accordingly, current research objectives are aimed at addressing these drawbacks and potential problems with the use of aluminum alloys on warships. One approach to minimizing these problems is to use barrier materials to protect aluminum superstructure materials from the heat generated in a shipboard fire. A number of light weight glass and ceramic fiber cloths, and intumescent organic coatings are available that might provide the required protection. However, prior to the selection and use of any such material, there is a need to evaluate the ability of a material to reduce heat transfer. This testing must be as simple and inexpensive as possible while still providing meaningful information.

A standard test, the ASTM E119 time temperature curve test (2), is designed to assess the ability of materials to prevent heat transfer to an underlying substrate. The test requires a 366 cm x 366 cm (12 ft x 12 ft) specimen and a large and expensive apparatus. The size of the sample required for the test and the cost and availability of the apparatus to conduct the test precludes its use as a screening test for the large number of materials that might be proposed for use on Canadian Naval ships.

A modified ASTM E119 apparatus has been developed and is in place at two laboratories in Canada: the Fire Research Section of the National Research Council of Canada and the Ontario Research Foundation in Toronto. This test requires 90 cm x 90 cm (3 ft x 3 ft) samples but the apparatus still requires a large facility. Testing costs range from $1000 to $1500 per test. These facilities can be contracted to test candidate barrier materials, but the tests are time consuming and use large sample sizes in addition to the rather significant cost per test.

However, the requirement still exists to evaluate barrier materials and consequently DREA has initiated a project, in conjunction with DMES 4, to develop a small scale test to be used both as a screening test and also for fire-safe materials research underway at DREA. Ideally, such a method should be simple, qualitative, require a minimum of complicated equipment, approximate the real situation as closely as possible, and be inexpensive to run. The test apparatus would be specifically designed to evaluate the ability of materials, such as fabrics, insulations or coatings, to protect substrates such as aluminum from heat and fire damage.

This paper describes a simple small scale test used at DREA. The results obtained on several barrier materials using this small scale apparatus are compared with those obtained at the Fire Research Section of the NRC using the modified ASTM E119 test to determine the degree of correlation between the results of the tests.

2.0 EXPERIMENTAL

2.1 Materials

The 6061 T651 aluminum alloy (NSN 9535-21-664-1319) was obtained from Drummond-McCall and Atlas Alloys as 0.64 cm (1/4 in) thick 122 x 244 cm (4 x 8 ft) or 122 x 366 cm (4 x 12 ft) sheets. Some typical mechanical and physical properties of this alloy are listed in Table 1 (3). Test specimens (coupons) for tensile and yield strength testing were cut to ASTM B557 (4) specifications. A coupon is shown diagrammatically in Figure 1.

The five glass and ceramic fiber barrier materials used for the testing are listed in Table 2 along with information on their chemical composition, thickness, and density. The five materials: Claretex 1925 B567, a woven glass fiber cloth commonly used as a replacement for asbestos as a lagging material; SilTemp, a quartz fiber/glass fiber woven cloth; Clarmatt 1200, a glass fiber batt material; PBI Startex 4N, a woven glass fiber cloth with a polybenzimadazole (PBI) fiber exterior; and PBI Startex 6N, a ceramic foam sandwiched between two woven glass fiber cloths with a PBI fiber exterior, are all available commercially.

With the exception of SilTemp which contains a high silicon quartz-type glass, all glass fibers were calcium aluminum silicates.

2.2 Equipment

6061 T651 aluminum coupons (see Figure 1) were heated in an oven for one hour at temperatures between 150° and 470°C, cooled to room

temperature, and the ultimate stress, yield stress, and Brinell hardness of each coupon were measured. The strength of the aluminum alloy was determined on an Instron testing machine using a 10000 kg load cell under load control. The Brinell hardnesses were measured on a Louis Small Brinell Hardness Tester.

2.2.1 Modified ASTM E119 Apparatus

The modified ASTM E119 apparatus used 90 cm x 90 cm samples. The time temperature curve used to control the heating of the oven is listed in Figure 2. The rate of heating of the oven is microprocessor controlled by a feedback loop between the oven and the burner; that is, thermocouples located in the oven monitor the rise in oven temperature which is compared to a series of setpoint temperatures. The gas flow to the burners (and consequently the temperature of the oven) is then adjusted automatically to meet the setpoint temperature.

2.2.2 Open and Closed Small Scale Test Apparatus

The open small scale apparatus is shown diagrammatically in Figure 3. It consists of a sample support and a Bunsen burner. The burner head was positioned 10 inches below the center of the barrier material surface. A diffusion propane/air flame was used as a source of heat. The temperature of the flame impinging on the sample was found to be between 780 and 810°C.

In an open system such as this, loss of heat by convection and radiation can be significant. To establish if these losses might effect the evaluation of the barrier materials, a closed 'oven-like' small scale apparatus was also constructed and trialed.

The closed small scale apparatus is shown diagrammatically in Figure 4. It was constructed from fire brick and heated with the same propane/air diffusion flame. The Bunsen burner head was positioned 10 inches below the center of the barrier material surface. The temperature of the flame impinging on the sample was again between 780 and 810°C. The oven temperature (area away from the flame) of the closed apparatus was approximately 700°C for all tests. In both the open and closed apparatus the temperature of the cold side of the aluminum panel (the side away from the heat source) was monitored with contact thermocouples positioned one inch on either side of the center of the panel and parallel to a side of the panel (see Figure 4). The time for the panel to reach 200°C was taken as the average of the times for the two thermocouples to reach 200°C.

Both the open small scale apparatus and the closed small scale apparatus used 30 x 30 cm (12 x 12 in) samples.

2.3 Testing Configurations

Four configurations of the barrier materials were tested using the modified ASTM E119 apparatus at the National Research Council to determine the optimum barrier material or combination of barrier materials for the protection of aluminum from heat damage. The configurations are shown diagrammatically in Figure 5 and are described below.

1) One side (hot side) protection of aluminum with one layer of materials a through d.

a) Startex 6N
b) Startex 4N
c) Claretex 1925 B567
d) SilTemp

2) Same as 1 above (a through d) but with two layers of each barrier material.

3) One side (hot side) protection as in 1 (a through d) but with a one inch layer of Clarmatt 1200 between the aluminum panel and the materials in 1 (a through d).

4) Two side protection of the aluminum panel with both the hot and cold side of the panel protected with one inch glass fiber batt and the materials in 1 (a through d).

The temperature rise on the cold side of the aluminum panel in the modified ASTM E119 test was monitored with three thermocouples located as shown in Figure 6. A test was terminated when the cold side of the aluminum panel reached 200°C.

The open small scale apparatus was evaluated using configurations 1 and 2, while the closed small scale test apparatus was evaluated using configurations 1, 2, and 3. All tests were terminated when the cold side of the panel reached 200°C.

3.0 RESULTS

3.1 Effect of Heat on the Strength of 6061 T651 Aluminum

Prior to evaluating the ability of the barrier materials to protect aluminum from heat damage, variations of the ultimate stress, yield stress, and Brinell hardness of 6061 T651 aluminum with temperature were determined.

Figures 7a through 7c show plots of the ultimate stress, yield stress, and Brinell hardness respectively against the temperature to which the panels were heated for one hour. The ultimate stress, yield stress, and Brinell hardness of 6061 T651 aluminum were all found to decrease significantly in room temperature tests after being exposed to temperatures between 250 and 300°C for one hour.

Figures 8a and 8b show plots of ultimate stress against Brinell hardness and yield stress against Brinell hardness respectively. Both the decrease in yield and ultimate stress correlate well with changes in Brinell hardness of the alloy. The results indicate that the decrease in strength of heat affected 6061 T651 aluminum alloy can be determined from a Brinell hardness measurement.

In the event of a fire on a ship with aluminum superstructure, the correlation between hardness and strength of aluminum alloys can be utilized to assess fire damage. Hardness measurements (Brinell or other hardness tests that can be related to Brinell hardness) of the superstructure can be made and used to determine the areas adversely affected by the fire. This would speed repair of the ship and avoid replacement of superstructure not weakened by the fire.

As a result of the deterioration in strength of this alloy when heated above 250°C, 200°C was chosen as the critical temperature, i.e., the temperature that panels should not exceed during the barrier tests. The protection given by a material or combination of materials was measured as the time it took for the cold side of the panel to reach this critical temperature.

3.2 Modified ASTM E119 Apparatus

The results of the ASTM E119 Time Temperature curve tests using the modified ASTM E119 apparatus are shown in Table 3. The results for each material represent the average of two tests on that material and configuration (see Figure 5).

The degree of protection provided by the barrier materials tested, i.e., the time required for the cold side of the aluminum panel to reach 200 °C, increased as the configuration was changed from 1 to 2 to 3 to 4. The best protection in test configuration 1 was provided by Startex 6N (14 minutes), while Startex 4N gave 13 minutes protection, Claretex 1925 B567 gave 10 minutes and SilTemp 9 minutes of protection. In configuration 2, Startex 4N provided 3 minutes more protection than Startex 6N (21 versus 18 minutes) while Claretex and SilTemp provided 16 and 13 minutes protection respectively.

The relative abilities of the Startex 4N and Startex 6N products

to protect the aluminum substrate from heat were reversed in configuration 3, where one inch of glass fiber batt was placed between the barrier material and the aluminum panel. Startex 6N plus one inch of glass fiber batt gave 52 minutes of protection while Startex 4N plus the glass fiber gave 50 minutes of protection. SilTemp and Claretex (plus one inch of glass fiber) each gave 48 minutes of protection.

Startex 6N gave the best protection in configuration 4 (90 min), followed by SilTemp (81 min), Startex 4N (72 min), and Claretex 1925 B567 (67 min). Startex 4N and Claretex 1925 B567 melted and burned through during the test and the aluminum panel melted.

It is interesting to note that the one inch glass fiber batt (used in configurations 3 and 4) significantly improved the performance of the four barrier materials tested. This can be attributed to the fact that the thermal resistance (R) of an insulating material is directly proportional to its thickness (D). Thermal resistance is defined as the temperature difference required to produce a unit of heat flux through a sample under steady state conditions (See Appendix A) and can be written as the ratio of the thickness of the sample to the thermal conductivity (λ) of the sample. The small difference in protection provided by the Startex materials and Claretex 1925 B567 and SilTemp might also be attributed to their difference in thickness. The Startex products are 2 mm thick, while Claretex 1925 B567 and SilTemp are 1 mm thick.

The results from the tests carried out in configuration 4 are difficult to explain. Prior to the tests it was felt that the barrier materials on the cold side of the panel would act to prevent escape of heat from the panel and lessen the time taken for the cold side of the aluminum panel to reach 200°C. However, the results indicate that the protection to the panel, as measured by the time for the cold side of the panel to reach 200°C, increased substantially.

3.3 Open Small Scale Apparatus

The results of the tests for these barrier materials using the open small scale test apparatus are shown in Table 4. Two test configurations of four barrier materials were tested (configurations 1 and 2 in Figure 5) and the results are the average of at least two tests on each material and configuration.

In configuration 1, the best protection was provided by Startex 6N, followed by Startex 4N, Claretex 1925 B567, and SilTemp. The relative ability of the barrier materials to protect aluminum did not change when configuration 2 was tested. However using configuration 2 (2 ply protection), the time for the cold side of the aluminum panel

to reach 200°C increased from 24 to 45 minutes for Startex 6N, from 21 to 40 minutes for Startex 4N, from 12 to 19 minutes for Claretex 1925 B567, and from 11 to 17 minutes for SilTemp.

The increase in the protection provided by the materials in configuration 2 can be attributed to the increase in thickness of the barrier and the resulting increase in thermal resistivity. However, the increase in protection was less than would be expected from doubling the thickness of the barrier material.

3.4 Closed Small Scale Apparatus

The results of the tests for the barrier materials using the closed small scale apparatus are shown in Table 5. Three configurations (1, 2, and 3 in Figure 5) of barrier materials were tested and the results are the average of two tests on each material and configuration.

As was found with the open small scale test, Startex 6N gave the best protection (26 min.) in configuration 1, followed by Startex 4N (25 min.), Claretex 1925 B567 (16 min,), and SilTemp (14 min.).

In configuration 2, the relative ranking of the barrier materials and hence the degree of protection did not change although the time required for the panel to reach 200°C increased for the four materials. The protection provided by Startex 6N increased to 95 minutes, Startex 4N to 67 minutes, Claretex 1925 B567 to 25 minutes, and SilTemp to 22 minutes.

The increase in protection measured for Startex 6N and Startex 4N in configuration 2 compared to configuration 1 was larger than would be predicted by theory. This was probably due to spaces between the plies of the barrier material. The air space between the plies would act to increase the apparent thermal resistivity of the materials and lead to longer protection times.

In configuration 3, i.e., one ply of the barrier material with one inch of glass fiber batt between the material and the aluminum panel, the cold side of the aluminum panel had not reached 200°C after 150 minutes for all materials. The Claretex 1925 B567 and Startex 4N materials melted and burned through during the test and it was observed that the underlying glass fiber melted. SilTemp did not melt but the underlying glass fiber batt did. The fact that the SilTemp material did not melt can be attributed to the difference in melting point of quartz (high silica) glass as opposed to calcium aluminum silicate glasses.

4.0 DISCUSSION

Although the protection provided to aluminum panels by a particular barrier material and/or configuration of barrier materials (as indicated by the time taken to heat the cold side of the panel to 200°C) varied from one test apparatus to another, the relative ratings assigned to the barrier materials tested in this study were consistent from one apparatus to another. This suggests that the relative ability of a material to prevent heat transfer is not overly sensitive either to the temperature or to the rate of temperature rise on the hot side of the panel because the small scale apparatus (both open and closed) did not have the same time-temperature profile as the modified ASTM E119 apparatus.

The large difference in protection for the barrier materials in configuration 2 using the modified ASTM E119 apparatus and the open and closed small scale apparatus may be due to several factors including the difference in the heat flux at the barrier surface as a result of the design of the small scale open and closed apparatus, and airgaps between the barrier materials and/or the material and the aluminum panel in the small scale tests.

The temperature on the hot side of the barrier increases with time in the modified ASTM E119 apparatus (see Figure 2). However, the temperature remains between 780 and 810°C (where the flame impinges on the barrier material) for both the open small scale apparatus and the closed small scale apparatus. The temperature in the oven of the closed small scale apparatus was approximately 700°C. As the time of a test increased, the temperature on the hot side of the barrier material continued to rise in the ASTM E119 apparatus, while it varied little with either small scale test apparatus.

It is also likely that airgaps between the plies of a material increased the apparent thermal resistivity of the material and therefore the protection it provided when tested in the small scale apparatus.

The open small scale test also appears to be a more severe test than the closed small scale test. The time taken for the aluminum panel to reach the critical temperature was greater for all materials tested in configurations 1 and 2 with the closed small scale test. This might be due to the poor ventilation of the closed small scale test. As was noted earlier a diffusion flame was used as a heat source and in the closed apparatus there may have been insufficient oxygen to ensure complete combustion of the fuel.

A small scale test apparatus having a premixed fuel/oxygen burner(s) and a microprocessor controlled oven temperature driven by a

thermocouple feedback loop would ensure more efficient combustion of the fuel. Further, loss of heat by convection and radiation would be minimized and result in a reproducible heat flux on the barrier materials during testing. The apparatus could be designed to allow proper venting of combustion gases and permit monitoring of volatiles released by barrier materials during a test. This would allow the identification and quantitation of hazardous volatiles produced when the various materials are exposed to high temperatures and thus provide additional information that could be used to rate materials.

Although there were measureable differences in the protection times found for a particular barrier material using the ASTM E119 apparatus and the small scale tests, the results indicate that a small scale apparatus can be used to determine the relative ability of barrier materials to prevent heat transfer to a substrate. A small scale apparatus would be particularly useful in comparisons of various materials, and allow tests to be performed promptly and inexpensively.

It should be noted that this report deals with the applicability of a small scale test apparatus to the evaluation of barrier materials to prevent heat transfer to aluminum and is not addressing which of the barrier materials tested in this report is best suited for Naval applications. The selection of a suitable barrier material would be based on a number of other criteria including weight, thickness, ease of attachment of the material to aluminum, production of hazardous volatiles, and cost.

5.0 CONCLUSIONS

This work demonstrates that a small scale test apparatus can be utilized to predict the relative ability of barrier materials to prevent heat transfer to aluminum and/or other superstructure materials. The results in Tables 3, 4, and 5 indicate that both the open and closed small scale tests give results for the materials evaluated that correlate well with those from the ASTM E119 test. That is, the ranking of the ability of the barrier materials to prevent heat transfer to aluminum is not dependent on the apparatus.

Although both the open and closed small scale tests give similar results for the materials evaluated and could be used to screen materials, a closed small scale apparatus would minimize the effect of variables such as heat loss through radiation and convection. Control of the oven temperature through the use of premixed fuel/air mixtures and microprocessor control of oven temperature would ensure reproducibility of time temperature profiles and facilitate comparison of results. A small scale test apparatus could also be designed to monitor volatiles produced during heating.

The correlation between the strength of aluminum alloys and their Brinell hardness (or hardness related to Brinell hardness) provides a quick and accurate way to determine if aluminum materials were affected by heat during a fire. This could speed the repair of a ship and avoid replacement of parts of the superstructure not affected.

Table 1

Typical mechanical and physical properties of 6061 T651 aluminum alloy.

Ultimate tensile strength	(Ksi)	45
	(kg/mm)	31.5
Yield strength 0.2 % offset	(Ksi)	40
	(kg/mm)	28
Hardness Brinell 500 kg load - 10 mm ball		95
Ultimate shear strength	(Ksi)	30
	(kg/mm)	21
Endurance limit	(Ksi)	14
	(kg/mm)	10
Melting range	582 - 652 °C	
Specific heat	896 J kg^{-1} K^{-1} (0.214 BTU lb^{-1} F^{-1})	
Thermal conductivity @ 25°C (T6 temper)	167 W $m^{-1}K^{-1}$ (96.5 BTU $h^{-1}ft^{-1}F^{-1}$)	

Table 2

Fire Barrier Materials

Material	Physical State	Chemical Comp.	Thickness (mm)	Density (g/cm^3)
Claretex 1925B567	woven sheet	Ca, Al, Si	1.0	0.7
SilTemp	woven sheet	Si, Ca(trace)	1.0	1.4
Startex 4N	mat on woven sheet	Ca, Al, Si int. & ext.	2.0	0.3
Startex 6N	mat on woven sheet	Al, Si (int) Ca, Al, Si (ext)	2.0	0.4
Clarmatt 1200	matted	Ca, Al, Si	25.4	0.2

TABLE 3

Results of the fire tests on the barrier materials acquired with the modified ASTM E119 apparatus at the Fire Research Section of the National Research Council.

	Material	Time to 200°C* (min)
Configuration 1 (1 ply)		
	Claretex 1925 B567	10
	SilTemp	9
	Startex 4N	13
	Startex 6N	14
Configuration 2 (2 ply)		
	Claretex 1925 B567	16
	SilTemp	13
	Startex 4N	21
	Startex 6N	18
Configuration 3**		
	Claretex 1925 B567	48
	SilTemp	48
	Startex 4N	50
	Startex 6N	52
Configuration 4***		
	Claretex 1925 B567	67
	SilTemp	81
	Startex 4N	72
	Startex 6N	90

* - time for the cold side of the aluminum to reach 200°C

** - 1 ply of the indicated material with 1 inch glass fiber batt between the material and the aluminum panel on the hot side

*** - as with configuration 3 but with cold side protected in the same manner as the hot side

TABLE 4

Results of the fire tests on the barrier materials acquired with the open small scale apparatus.

	Material	Time to 200°C* (min)
Configuration 1 (1 ply)		
	Claretex 1925 B567	12
	SilTemp	11
	Startex 4N	21
	Startex 6N	24
Configuration 2 (2 ply)		
	Claretex 1925 B567	19
	SilTemp	17
	Startex 4N	40
	Startex 6N	45

* - time for the cold side of the aluminum panel to reach 200°C.

TABLE 5

Results for the candidate barrier materials acquired with the closed small scale apparatus.

	Material	Time to 200°C* (min)
Configuration 1 (1 ply)		
	Claretex 1925 B567	16
	SilTemp	14
	Startex 4N	25
	Startex 6N	26
Configuration 2 (2 ply)		
	Claretex 1925 B567	25
	SilTemp	22
	Startex 4N	67
	Startex 6N	95
Configuration 3**		
	Claretex 1925 B567	>150
	SilTemp	>150
	Startex 4N	>150
	Startex 6N	>150

* - time for the cold side of the aluminum panel to reach 200°C

** - 1 ply of the indicated material with 1 inch of fibreglass batt between the material and the aluminum panel

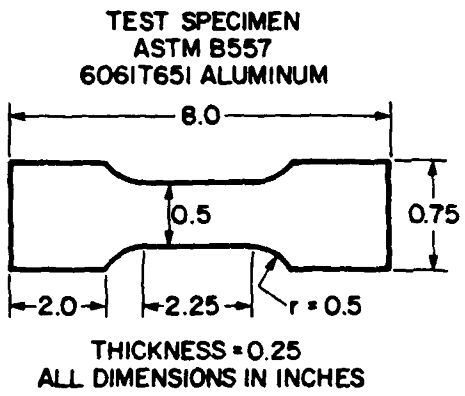

Figure 1 - Dimensions of 6061 T651 aluminum tensile test specimen (coupon) prepared to ASTM B557 specifications.

Figure 2 - Standard ASTM E119 Time-Temperature Curve for control of fire tests.

TIME h:min	TEMPERATURE °C	°F	AREA ABOVE 20°C BASE °C-h
0.00	20	68	0
0.05	538	1000	22
0.10	704	1300	72
0.15	760	1399	131
0.20	795	1462	194
0.25	821	1510	260
0.30	843	1550	328
0.35	862	1584	397
0.40	878	1613	468
0.45	892	1638	540
0.50	905	1661	613
0.55	916	1681	687
1.00	927	1700	762
1.05	937	1718	838
1.10	946	1735	915
1.15	955	1750	993
1.20	963	1765	1071
1.25	971	1779	1150
1.30	978	1792	1229
1.35	985	1804	1309
1.40	991	1815	1390
1.45	996	1826	1471
1.50	1001	1835	1553
1.55	1006	1843	1635
2.00	1010	1850	1717
2.10	1017	1862	1882
2.20	1024	1875	2049
2.30	1031	1888	2217
2.40	1038	1900	2386
2.50	1045	1912	2556
3.00	1052	1925	2728
3.10	1059	1938	2900
3.20	1066	1950	3074
3.30	1072	1962	3249
3.40	1079	1975	3425
3.50	1086	1988	3602
4.00	1093	2000	3780
4.30	1114	2038	4322
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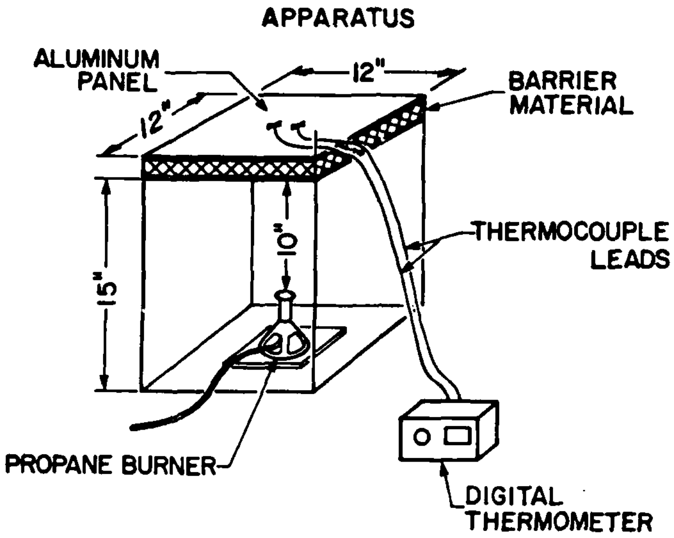

Figure 3 - Diagrammatic representation of the small scale open apparatus. Position of the thermocouples is the same as that shown in Figure 4.

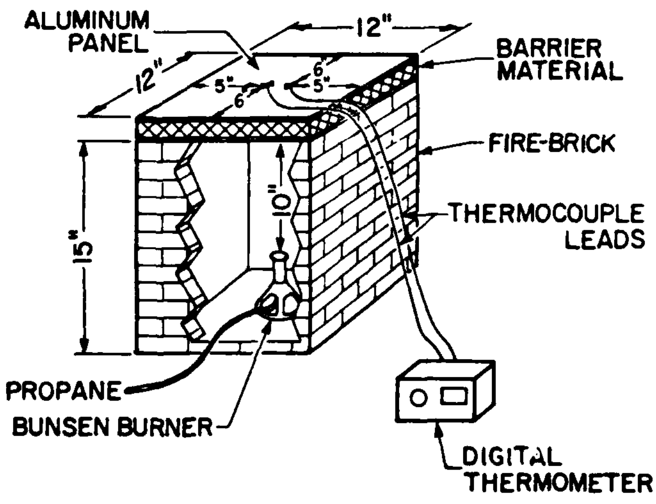

Figure 4 - Diagrammatic representation of the small scale closed apparatus showing the position of the thermocouples on the aluminum panel.

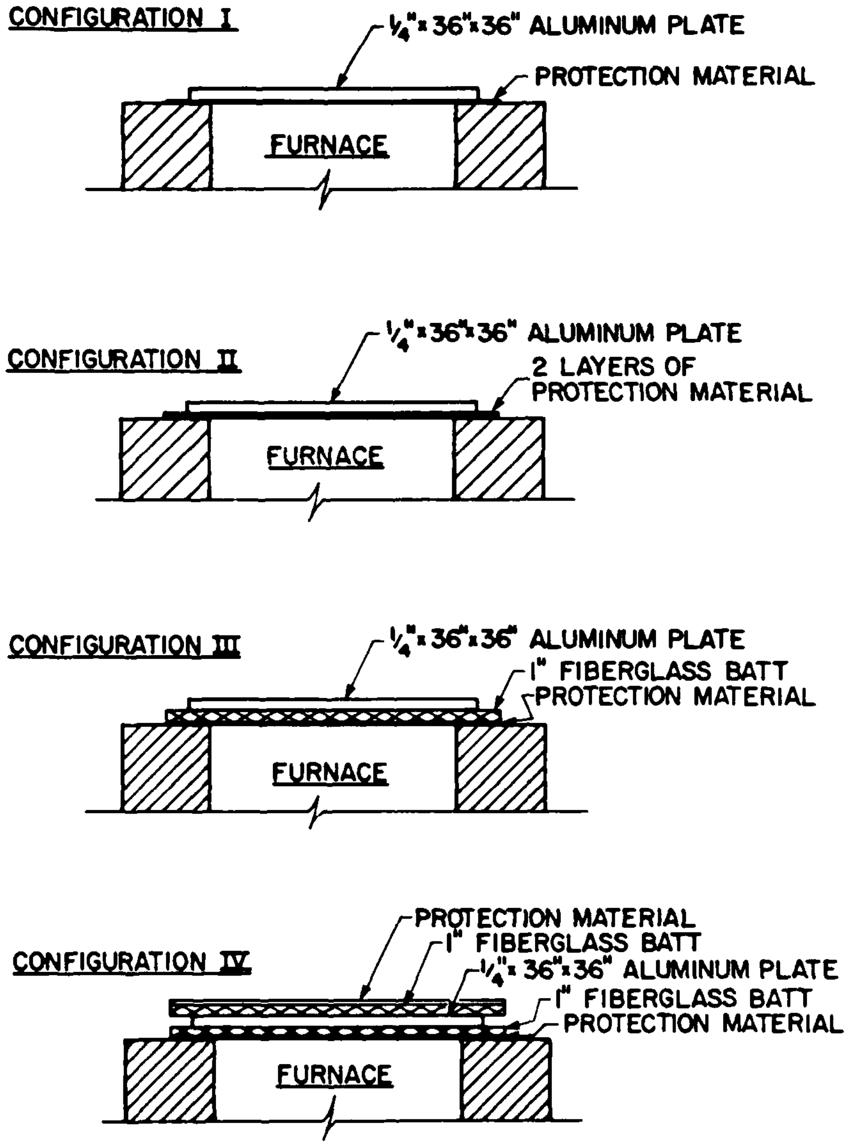

Figure 5 - Diagrammatic representations of the four configurations of materials used in the modified ASTM E119 tests at the National Research Council.

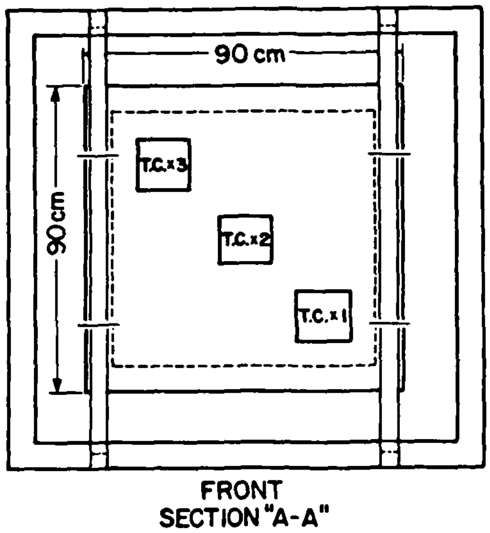

Figure 6 - Location of the three thermocouples in the modified ASTM E119 time-temperature tests.

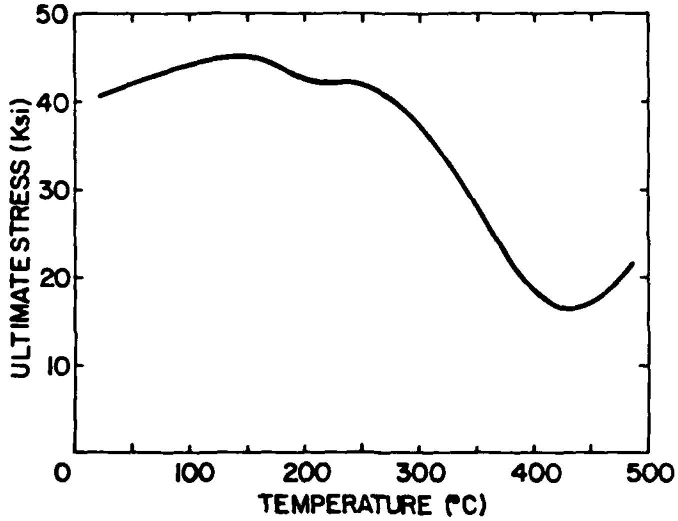

Figure 7a - Plot of ultimate tensile strength of 6061 T651 aluminum test coupons against the temperature to which the coupons had been heated for one hour. The specimen was cooled to room temperature prior to the test.

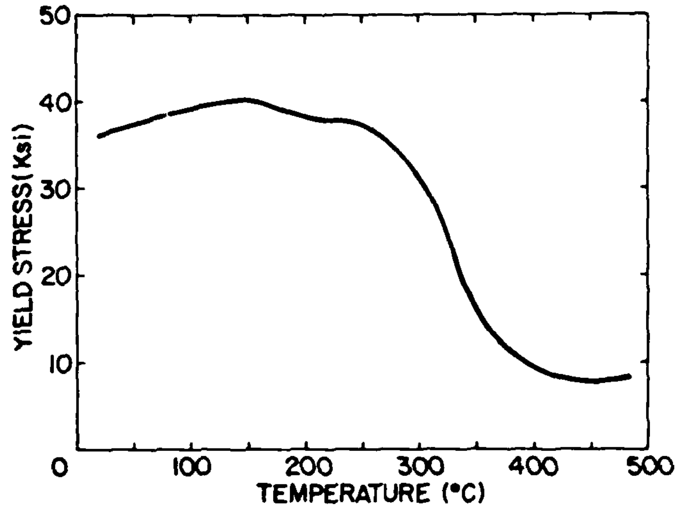

Figure 7b - Plot of yield strength of 6061 T651 aluminum test coupons against the temperature to which the coupons had been heated for one hour. The specimen was cooled to room temperature prior to the test.

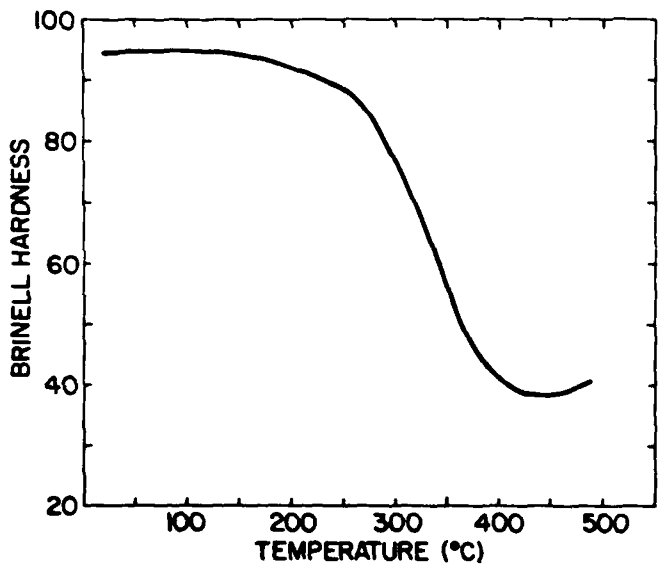

Figure 7c - Plot of the Brinell hardnesses of 6061 T651 aluminum coupons against the temperature to which the coupons had been heated for one hour. The coupon was at room temperature when the hardness measurement was made.

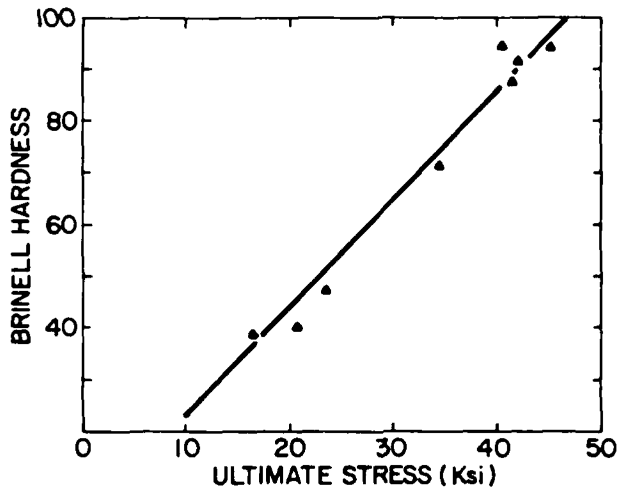

Figure 8a - Plot of the Brinell Hardness of 6061 T651 aluminum coupon against the ultimate tensile strength of the coupon.

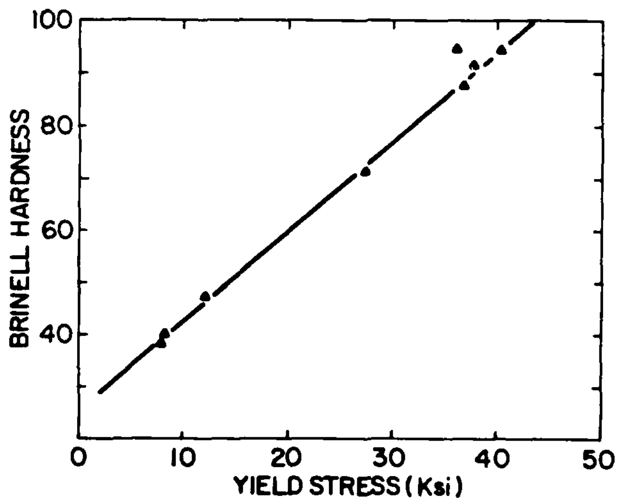

Figure 8b - Plot of the Brinell Hardness of 6061 T651 aluminum coupon against the yield strength of the coupon.

Appendix A

Definitions of terms used in conjunction with materials used to prevent heat transfer.

1) Thermal Resistance (R) - Under steady state conditions, the temperature difference required to produce a unit of heat flux through a specimen. For a flat slab this can be written as;

$$R = A\ (t_1 - t_2)/Q = 1/T = D/l \tag{1}$$

where R is thermal resistance in units of degrees Kelvin (K) meter squared (m^2) per Watt (W), A is area, t_1 and t_2 are the temperatures of the hot and cold side of the material respectively, Q is the rate of heat flow, T is thermal conductance, D is thickness, and l is the thermal conductivity.

2) Thermal Conductance (T) - Under steady state conditions, the heat flux required to produce a unit temperature difference through a specimen. For a flat slab it can be written as;

$$T = Q/A(t_1 - t_2) = l/D \tag{2}$$

where T is in units of $Wm^{-2}K^{-1}$ and is the inverse of thermal resistance.

3) Thermal Conductivity (l) - Under steady state conditions, the heat flux per unit temperature gradient in the direction perpendicular to the isothermal surface. For a flat slab it can be written as;

$$l = QD/A(t_1 - t_2) = D/R \tag{3}$$

and is measured in units of $Wm^{-1}K^{-1}$.

4) Thermal Resistivity (r) - Under steady state conditions, the temperature gradient perpendicular to the isothermal surface per unit heat flux. For a flat slab it can be written as;

$$r = A(\ t_1 - t_2)/QD = 1/l = R/D \tag{4}$$

and is measured in units of KmW^{-1}. It is the inverse of thermal conductivity.

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(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATING ACTIVITY Defence Research Establishment Atlantic	2a. DOCUMENT SECURITY CLASSIFICATION Unclassified 2b. GROUP
3. DOCUMENT TITLE Development of a Small Scale Test Apparatus for the Evaluation of Thermal Barrier Materials	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Technical Communication	
5. AUTHOR(S) (Last name, first name, middle initial) Hiltz, J.A. and Veinot, D.E.	
6. DOCUMENT DATE April 1987	7a. TOTAL NO. OF PAGES 29 / 7b. NO. OF REFS 4
8a. PROJECT OR GRANT NO.	9a. ORIGINATOR'S DOCUMENT NUMBER(S) DREA TECHNICAL COMMUNICATION 87/307
8b. CONTRACT NO.	9b. OTHER DOCUMENT NO.(S) (Any other numbers that may be assigned this document)
10. DISTRIBUTION STATEMENT	
11. SUPPLEMENTARY NOTES	12. SPONSORING ACTIVITY Defence Research Establishment (A)

13. ABSTRACT

A small scale test apparatus has been constructed and used to evaluate the relative ability of four thermal barrier materials to protect aluminum from heat damage. The apparatus used 30 x 30 cm (1 ft x 1 ft) x 0.64 cm (0.25 in) aluminum panels. Several configurations of the glass and ceramic fiber cloth barrier materials (Startex 6N, Startex 4N, SilTemp, and Claretex 1925 B567) were tested to determine the degree of protection provided by the thermal barrier materials. The results obtained with the small scale tests have been correlated with those obtained with a modified ASTM E119 apparatus at the Fire Research Section of the National Research Council of Canada. Although the results from the small scale tests do not compare with those from the ASTM E119 test in an absolute sense, they give the same relative ranking of the ability of the barrier materials to protect aluminum from heat damage. This suggests that inexpensive small scale testing can be used to screen and rank the ability of different materials and combinations of materials to protect an aluminum substrate from heat damage.

DSIS 78-070

Unclassified

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KEY WORDS

evaluation
thermal barrier
apparatus
glass and ceramic fiber cloths
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